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Published in:
Conference on Lasers and Electro-Optics, 2009 and 2009 Conference on Quantum electronics and Laser Science Conference. CLEO/QELS 2009.

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Larsson, D., Greve, A., Hvam, J. M., Boisen, A., & Yvind, K. (2009). Self-mixing interferometry in VCSELs for nanomechanical cantilever sensing. In *Conference on Lasers and Electro-Optics, 2009 and 2009 Conference on Quantum electronics and Laser Science Conference. CLEO/QELS 2009.* (pp. 1-2). IEEE.

Self-mixing interferometry in VCSELs for nanomechanical cantilever sensing

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Abstract: We have investigated optical read-out of uncoated polymer micrometer-sized cantilever sensors by self-mixing interference in VCSELs for single-molecule gas sensing. A resolution ~0.2 nm is measured, which is much better than current methods.

OCIS codes: (280.3420) Laser sensors, (250.7260) Vertical cavity emitting lasers

1. Introduction

Self-mixing interference (SMI) in diode lasers has been widely used in various sensing applications such as velocimetry and ranging measurements [1]. Feedback from an object outside the laser cavity alters the condition for threshold gain and phase, thereby changing the threshold, the slope efficiency, the output intensity and the spectrum. We specifically address the application of optical read-out for monitoring the deflection of micrometer-sized polymer cantilever sensors, which are promising candidates for inexpensive, mass-producible and miniaturized sensors to monitor single molecules of chemical and biological analytes [2] (nanonoses). The standard/prevailing read-out of cantilevers is performed with the optical lever method, which is bulky, expensive and not well suited for polymer cantilevers with a reflectivity of ~5 % in air. In general cantilevers need to be coated with a layer of gold to increase the reflectivity [3] for the optical lever method. This introduces unwanted bimorph effects and increases surface complexity. Here we show that SMI in VCSELs is sensitive enough to measure a few nanometers deflection of polymer cantilevers with high resolution. Since the semiconductor laser can be monolithically integrated with a photo detector (PD) [4] the entire sensing system can be very compact, robust and simple. There is also the possibility to use the modulation of the laser voltage as a signal, as shown in Fig. 2a. However, in that case lock-in detection may be needed [5]. The surface emission makes it possible to make 1D and 2D arrays of VCSELs matching an array of cantilevers, and the two chips can be bonded together, so that no post alignment is necessary.

2. Measurements

A single-mode 850 nm top-emitting VCSEL (Advanced Optical Components) is used as the self-mixing element. The threshold current of the solitary laser is ~0.95 mA, while the slope efficiency is ~0.33W/A. The cantilevers, made of Topas (400x100x4.5 μm^3) have been glued to a stage facing the laser diode and the distance was varied by means of a micrometer screw from 35 to 250 µm, see Fig. 1a. The signal is obtained by moving the stage with a piezo actuator with 10 nm minimum step size (the expected angle of deflection under bending is very low, <0.24mrad, and thus can be neglected). The laser light is detected by a PD (Thorlabs PDA100EC) and the voltage variations are read from a digital multimeter. Lateral alignment of cantilever and laser is done by imaging the beam onto a Si CCD-camera. To decrease the influence of air flow on the displacement of the cantilevers, the set-up is shielded by a box of Plexiglass.

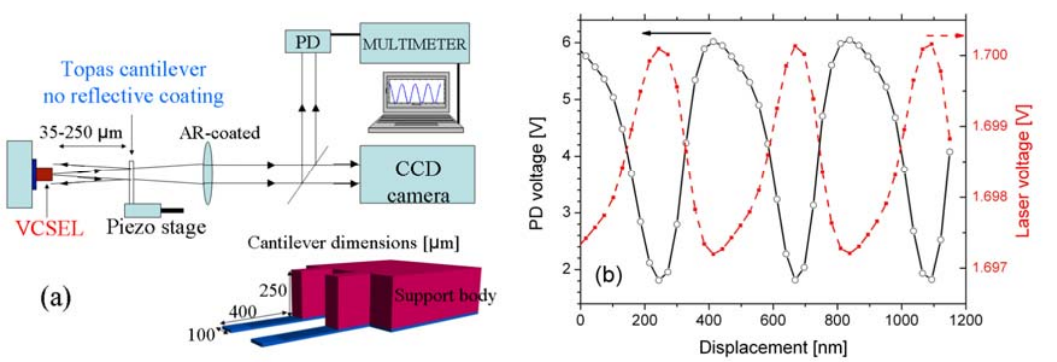

Fig. 1. (a) Schematic of measurement set-up. PD: Thorlabs PDA100EC photodiode with transimpedance amplifier. OSA/ESA: Optical/Electrical Spectrum Analyzer. (b) PD voltage and laser voltage signal from topas cantilever at a distance of ~35 µm and a current of 0.98 mA.

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Fig. 1b presents the output signal from the PD vs. the piezo's displacement of the cantilever at a distance of ~35 µm and a laser drive current of 0.98 mA. The sensitivity can be linearized around the steepest slope and can be as high as 45 mV/nm in a range of ±25 nm. The error is ±10 mV corresponding to ~0.2 nm. Our measurements of the visibility of the power emitted from the top mirror vs. the laser current are shown in Fig. 2a. Three distinct regions can be identified: the peak around the threshold, originating from the changes in threshold current, I_{th}, a dip shortly after and a constant level. Analytical approximations of the visibility found in e.g. ref. 1 do not reproduce the dip since they do not include the changes in the fractional output power due to the feedback and given by [6]

$$F(z) = \frac{T_{eff}(z)}{(1-R_{eff}(z)) + \sqrt{\frac{R_{eff}(z)}{R_1}}(1-R_1)}$$

where R_{eff} and T_{eff} are the effective power reflectivity and transmittivity from the top DBR, while R_1 is the reflectivity of the bottom DBR of the VCSEL. Because of the small transmittivities of the VCSEL mirrors the small changes in R_{eff} caused by the feedback lead to large changes in T_{eff} causing large changes in F. Since the output from VCSELs is highly non-symmetric the relative changes in fractional power are much larger for the bottom DBR (in the top-emitting case). The phase of the changes in F with respect to z is also important. They are out of phase with the changes in threshold gain on the side facing the feedback, giving rise to a dip in the visibility vs. current relation, whereas the changes in F on the opposite side are in phase. The experimental change of the slope efficiency, η_d, due to the change in fractional output power through the top DBR is as high as 10 % at a feedback distance of ~35 µm. The dip in visibility is located at the crossing of the LI-curves at approximately

$$I_{V=0} = \frac{\eta_d^{\max} I_{th}^{\max} - \eta_d^{\min} I_{th}^{\min}}{\eta_d^{\max} - \eta_d^{\min}}$$

while the visibility at high currents is only given by the change in differential efficiency

$$V_{I\to\infty} = \left| \frac{\eta_d^{\max} - \eta_d^{\min}}{\eta_d^{\max} + \eta_d^{\min}} \right|$$

which is also measured experimentally. In general the highest modulation depth is monitored through the high reflectivity mirror while the cantilever is placed on the opposite side of the VCSEL. The laser voltage visibility, related to the changes in Fermi levels, is also plotted in Fig. 2a. Fig. 2b shows how the visibility of the output power drops with decreased feedback strength as the cantilever is moved away from the laser, caused by the diverging laser beam.

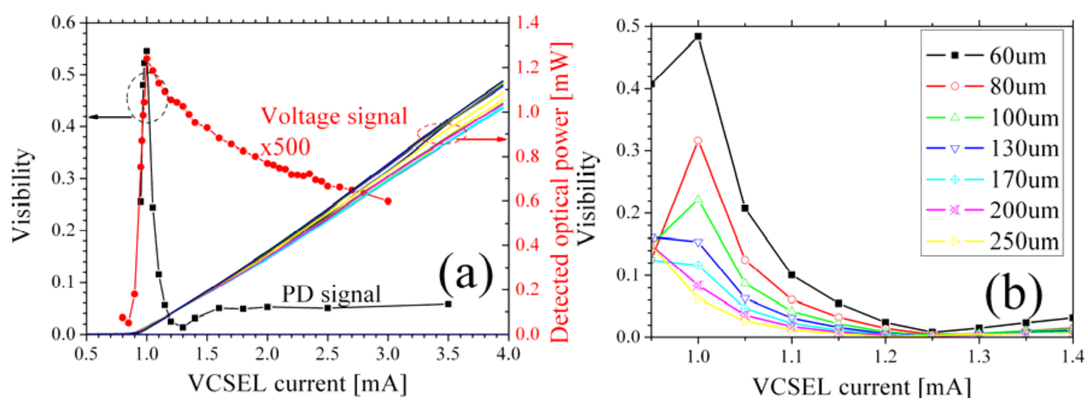

Fig. 2. (a) Visibility of photodetector and laser voltage, and detected power level vs. VCSEL current at an external cavity length of ~35 µm. (b) Visibility of photodetector vs. VCSEL current for different external cavity lengths.

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